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CHANNEL ISLANDS TELEVISION PROGRAMME LINKS: THE DESIGN OF A U.H.F. FEED ANTENNA FOR A 9·14 m DIAMETER PARABOLOIDAL REFLECTOR

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Summary

The design of a feed antenna for a paraboloidal reflector is discussed in relation to the optimization of the gain and the likely side-lobe level. The design has been realized in a practical feed antenna but the performance of the complete antenna has not yet been assessed experimentally.

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1. Introduction

Alderney, the most northerly of the Channel Islands, provides the site for picking up u.h.f. television programmes radiated from Stockland Hill (Devon) and passing them on to Fremont Point, the main u.h.f. transmitting station on Jersey. Two of the u.h.f. receiving antennas on Alderney are 9·14 m (30 ft) diameter paraboloidal reflectors, erected by the British Post Office some time before 1965. These antennas passed into the jurisdiction of the Guernsey States Telecommunication Board and are now the responsibility of the IBA. No maintenance work has been carried out on them since some time prior to 1974 and they are showing severe corrosion.

At the end of 1977 the IBA made a proposal to replace the upper reflector and feed antenna, retaining the existing tripod after strengthening. The lower reflector and tripod were to be dismantled. The proposal was suspended on account of financial considerations but seems likely to be implemented in 1979 or 1980. This report describes the design of the replacement feed antenna which was undertaken jointly for the IBA and the BBC.

2. The paraboloidal reflector

The equation describing the surface of a paraboloid is

$$x^2 + y^2 = 4fz$$

where f is the focal length. The principal section in the x, z plane, i.e. the section containing the axis of revolution, is shown in Fig. 1.

Two important parameters for a paraboloid are the ratio of the focal length, f, to the diameter D and the angle, ψ_0, subtended at the focus by the portion of the paraboloid between the axis and the outer edge. These parameters are related by the equation

$$\tan \psi_0 = \frac{1}{2}\left(\frac{D/f}{1 - D^2/16f^2}\right)$$

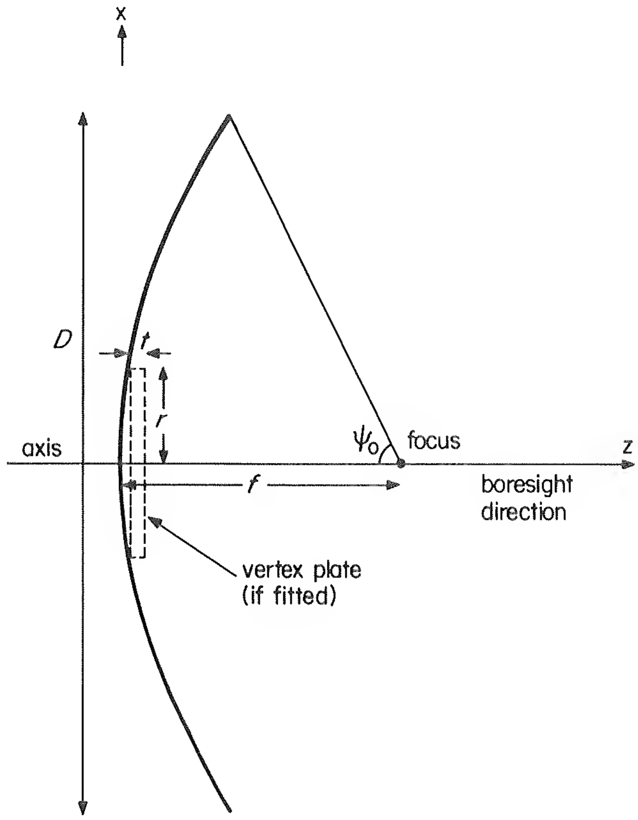

Fig. 1 - Geometry of the paraboloid

Rearranging gives the relation

$$\frac{D}{f} = 4 \tan \frac{\psi_0}{2}$$

It is assumed that the paraboloidal reflector will have a diameter of 9·14 m (30 ft) and a focal length of 3·658 m (12 ft). Thus the focal length/diameter ratio will be 0·4 and the angles subtended by the edges of the reflector at the focus will be ±64°.

3. The theoretical efficiency of a paraboloidal reflector antenna

The efficiency of a paraboloidal reflector antenna is defined as the factor by which the gain of a uniformly-illuminated, co-phased aperture must be multiplied to give the gain of the actual antenna. This overall efficiency may be regarded as being the product of a number of component efficiencies.

$$\eta = \eta_1 \cdot \eta_2 \cdot \eta_3 \cdot \eta_4 \cdot \eta_5 \cdot \eta_6 \cdot \eta_7 \cdot \eta_8 \cdot \eta_9 \cdot \eta_{10} \cdot \eta_{11}$$

where η_1 = illumination efficiency dependent on feed illumination law
η_2 = radiation or spill-over efficiency
η_3 = loss due to paraboloid profile inaccuracy
η_4 = loss due to blockage created by the feed, coaxial cable and supports
η_5 = loss due to back lobe of feed
η_6 = loss due to vertex plate for matching
η_7 = ohmic loss in the feed, the coaxial cable and in the reflector by skin effect
η_8 = loss in the radome, if any, of feed or of antenna
η_9 = loss due to the transparency of the reflector, if any
η_{10} = loss due to cross-polarization
η_{11} = loss due to misalignment of the feed

All these efficiencies have values between 0 and 1, except η_5, which can be greater than one.

It is convenient to take η_1 and η_2 together in order to optimize the product; this is considered in Section 4 together with η_5. In the present application the frequency is low so that η_3 and η_9 should both be near to unity. No randome is planned so that η_8 is also unity. The remaining parameters are considered as they arise.

4. Specification of the radiation pattern of the feed antenna

It is normal practice to make the illumination of the reflector less at the edges than at the centre. The ratio chosen depends on whether maximum gain or very low side lobes are required. In the present application it is thought that maximum gain will give sufficiently low side lobes.

Let the power radiation pattern of the feed be represented by

$$G_f(\psi) = G_0 \cos^n \psi \qquad 0 \leqslant \psi \leqslant \pi/2$$

$$= 0 \qquad \psi > \pi/2$$

where G_f is the gain at an angle ψ off the axis of the feed, G_0 is the axial gain and n is an integer.

The efficiency of the feed, expressed relative to a uniform co-phased illumination up to the edge of the reflector and zero beyond it, may be shown to be[1]

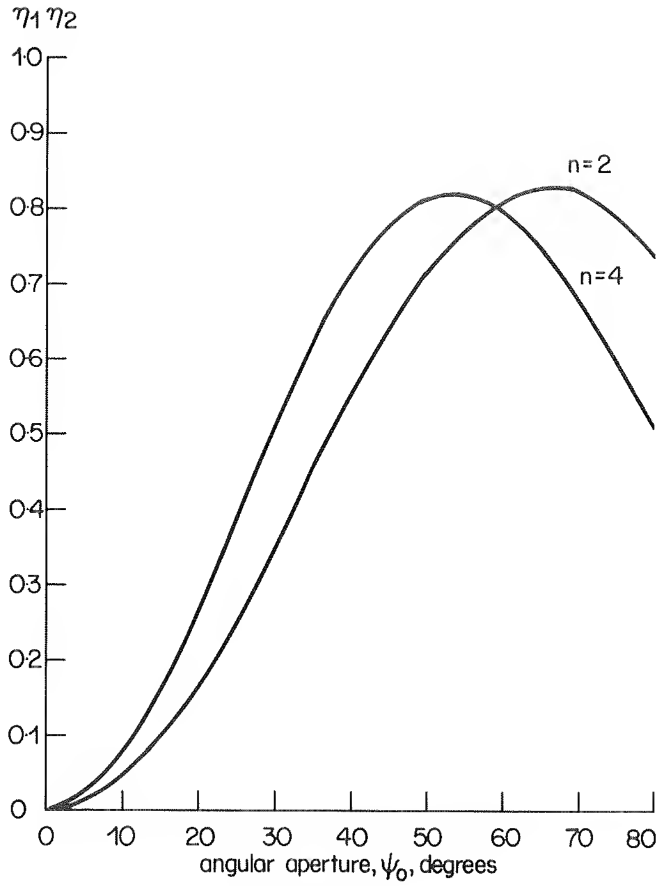

Fig. 2 - Illumination and spill-over efficiencies

$$\eta_1 \cdot \eta_2 = 2(n+1)\left[\cos\frac{\psi_0}{2}\int_0^{\psi_0} \cos^{n/2}\psi \tan\frac{\psi}{2}\,d\psi\right]^2$$

This expression has an explicit solution for even values of n and some of these are shown graphically in Fig. 2, which was taken from Reference 1. It may be seen that for an angular aperture ψ_0 of 64° the value of n giving a maximum efficiency, $\eta_1 \cdot \eta_2$, of around 0·83 is about 2. The required gain function for the feed is therefore,

$$G_f(\psi) = G_0 \cos^2 \psi$$

and the amplitude response is cos ψ. The exact shape of the pattern is not unduly critical. Thus, if the feed antenna has instead a $\cos^2 \psi$ amplitude response (n = 4) the efficiency, $\eta_1 \cdot \eta_2$, drops to 0·75, for ψ_0 = 64°, corresponding to a drop of 0·4 dB in the gain of the composite antenna. Both these patterns are shown in Fig. 3 and may be used to judge the patterns of an actual antenna.

It should be noted that no further correction of these patterns is required. Some references

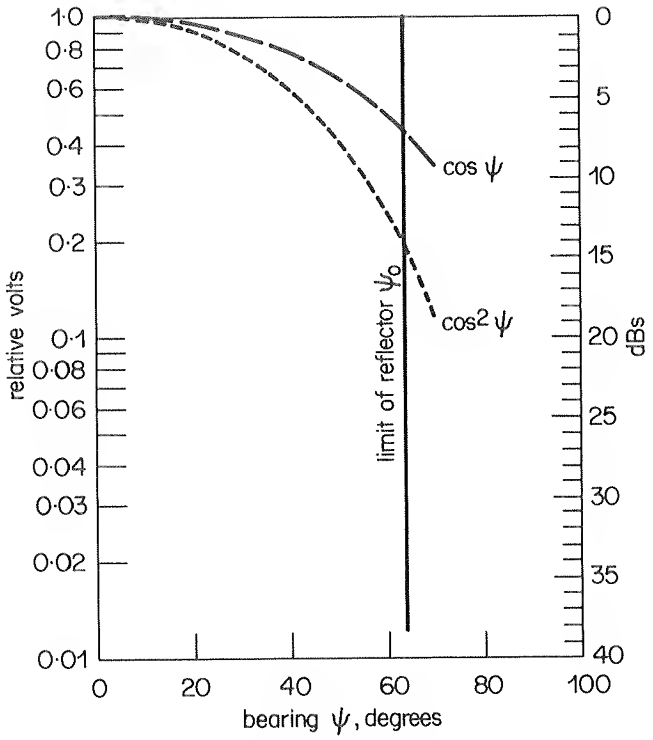

Fig. 3 - Theoretical feed antenna patterns

consider the distribution of current over the aperture and then convert this into the radiation pattern of the feed antenna by means of a divergence or space attenuator factor. This factor has been included in the analysis leading to the curves of Fig. 2, the illumination being reduced at the edge of the reflector on account of the greater distance travelled.

So far it has been assumed that the feed antenna has no backward radiation, i.e.

$$G_f(\psi) = 0 \text{ for } \psi > \pi/2$$

A practical antenna will have some backward radiation and this may be considered in three ways.

(i) The power radiated by the feed antenna and not intercepted by the reflector is increased, i.e. the radiation efficiency is decreased.

(ii) In the boresight direction, the back radiation will add vectorially to the main beam, increasing or reducing the gain by a small amount. Since the antenna is required to be wide-band, the gain cannot be optimized in this respect.

(iii) Away from the main beam, the backward radiation will be superimposed on the side lobes and may raise the general side-lobe level.

The following table gives the magnitudes of these effects for two levels of backward radiation and the size of reflector under consideration.

TABLE 1

	Relative level of back lobe	
	−20 dB	−10 dB
Reduction of radiation efficiency, η_2	1%	10%
Perturbation of power gain	±1·4%	± 4·4%
Additional side-lobe amplitude (ϕ is the azimuthal angle)	0·007 cosϕ	0·022 cosϕ

The most important aspect would seem to be the effect on the side-lobe level and it is suggested that the front-to-back ratio of the feed antenna radiation pattern should be at least 20 dB.

5. Specification of the impedance match of the composite antenna

The feed antenna will be connected to a low-noise head amplifier through about 5·5 m of semi-airspaced coaxial cable. The equivalent length of air-spaced line is 7 m so that any mismatch of this cable will give rise to an amplitude variation repeating at intervals of 21 MHz. Thus although it would put a small slope across one channel, the principal effect would be on the relative levels of the channels. The delay will be too short to give significant delayed images.

The head amplifier to be used has not yet been chosen, but a typical input v.s.w.r. would be 2:1 for a single amplifier and better than this for an Engelbrecht pair. If the feed antenna is allowed a maximum reflection coefficient of 20% (v.s.w.r. = 1·5), the maximum amplitude variation is ±0·6 dB and this should be acceptable. The maximum power reflection coefficient is 0·04 so that the matching efficiency is at worst 0·96. The loss in 5·5 m of ½ inch foam cable is about 0·4 dB but it is preferred to consider this separately from the antenna. Other ohmic losses will be negligible so that

$$\eta_7 = 0{\cdot}96$$

The above analysis assumes that the feed antenna can be matched to these limits in the presence of the reflector. Consideration of the use of a vertex plate and the associated efficiency factor, η_6, is given in Section 7.6.

6. Cross-polarization

The geometry of the paraboloid is such that cross-polarized components of field are excited in off-axis directions. The cross-polarized radiation pattern has zeroes in the principal E- and H-planes and four maxima lying in the planes at 45° to the principal planes.[1] Although no detailed analysis has been performed, it is not expected either that the side-lobe level will be significantly affected in any important direction or that the efficiency will be materially affected, i.e. we assume $\eta_{10} = 1$.

7. A practical feed antenna

7.1. General considerations

The antenna was required to receive four colour television programmes in the frequency range 486 MHz – 574 MHz. The feed antenna used with the original reflectors was a combined v.h.f./u.h.f. design manufactured by Jaybeam Ltd. to an IBA specification. It is a four-element yagi antenna mounted on a metal boom with some elements above the boom and some below. Various measurements of the gain of the reflector/feed combination indicated a value about 4 dB less than might have been expected on the highest u.h.f. channel of interest (channel 33) i.e. an efficiency excluding feeder losses of only 22%. It was supposed that part of the deficiency was attributable to lack of symmetry in the H-plane. In order to test this hypothesis an experimental feed u.h.f. antenna was made with due regard to symmetry. This was also a Yagi antenna comprising one director, a driven dipole and two reflector elements. With the experimental feed fitted the gain of the paraboloid at the highest frequency channel was found to be on average 3·8 dB greater, corresponding to an efficiency of just over 50%. The generally accepted maximum practical value is 55%.

The experimental feed antenna had two disadvantages for service use. First, it was necessary to run the co-axial cable from it along one of the stays. This would not have resulted in any significant increase of aperture blocking but it would have increased the length of feeder between antenna and head amplifier. It was also thought that a redesign could yield better weather protection and possibly slightly better radiation patterns.

7.2. Description

The antenna* is simply a driven dipole with a wire mesh reflector mounted on a tubular metal boom on the axis of the paraboloid. Care has been taken to preserve symmetry in both E- and H-planes. The co-axial cable to the feed is low-loss foam-dielectric cable and passes inside the boom. The boom is held horizontally by four 'Parafil' stays which will be adjusted to give fine control of the direction of the main beam. 'Parafil' is p.c.v.-covered terylene, and should not give any significant aperture blocking even in wet conditions. The system is designed so that the feed antenna can be replaced without removing the stays.

Fig. 4 shows a photograph of the feed antenna.

7.3. Radiation patterns and gain

The E-plane and H-plane radiation patterns are shown in cartesian form in Fig. 5 and in polar form in Fig. 6. Fig. 5 also shows the r.m.s. pattern, i.e. the equivalent cylindrically-symmetrical pattern, this being used to assess the efficiency of the feed. The efficiency of illumination, η_1, was deduced by comparison with theoretical $\cos\psi$ and $\cos^2\psi$ patterns. The spill-over efficiency, η_2, was determined by integration of the power falling on the reflector in relation to the total power. As a control a similar procedure was followed for the

* The detailed design and matching of this antenna was carried out by D.J. Darlington.

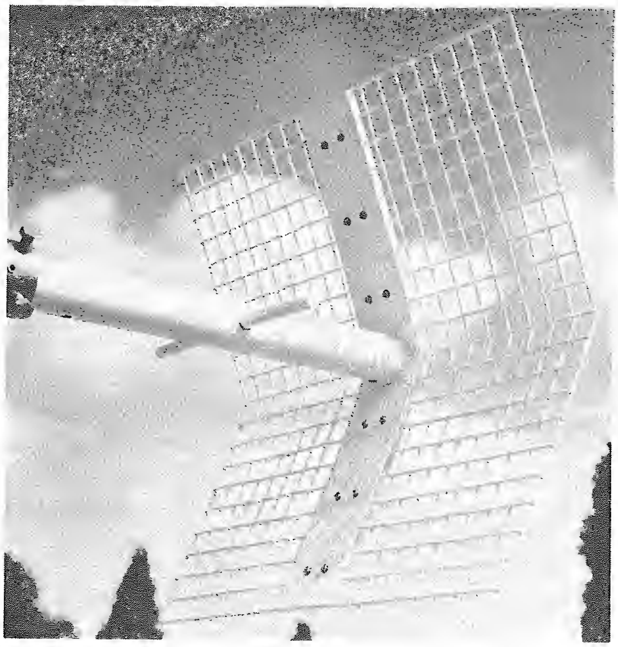

Fig. 4 - A practical feed antenna

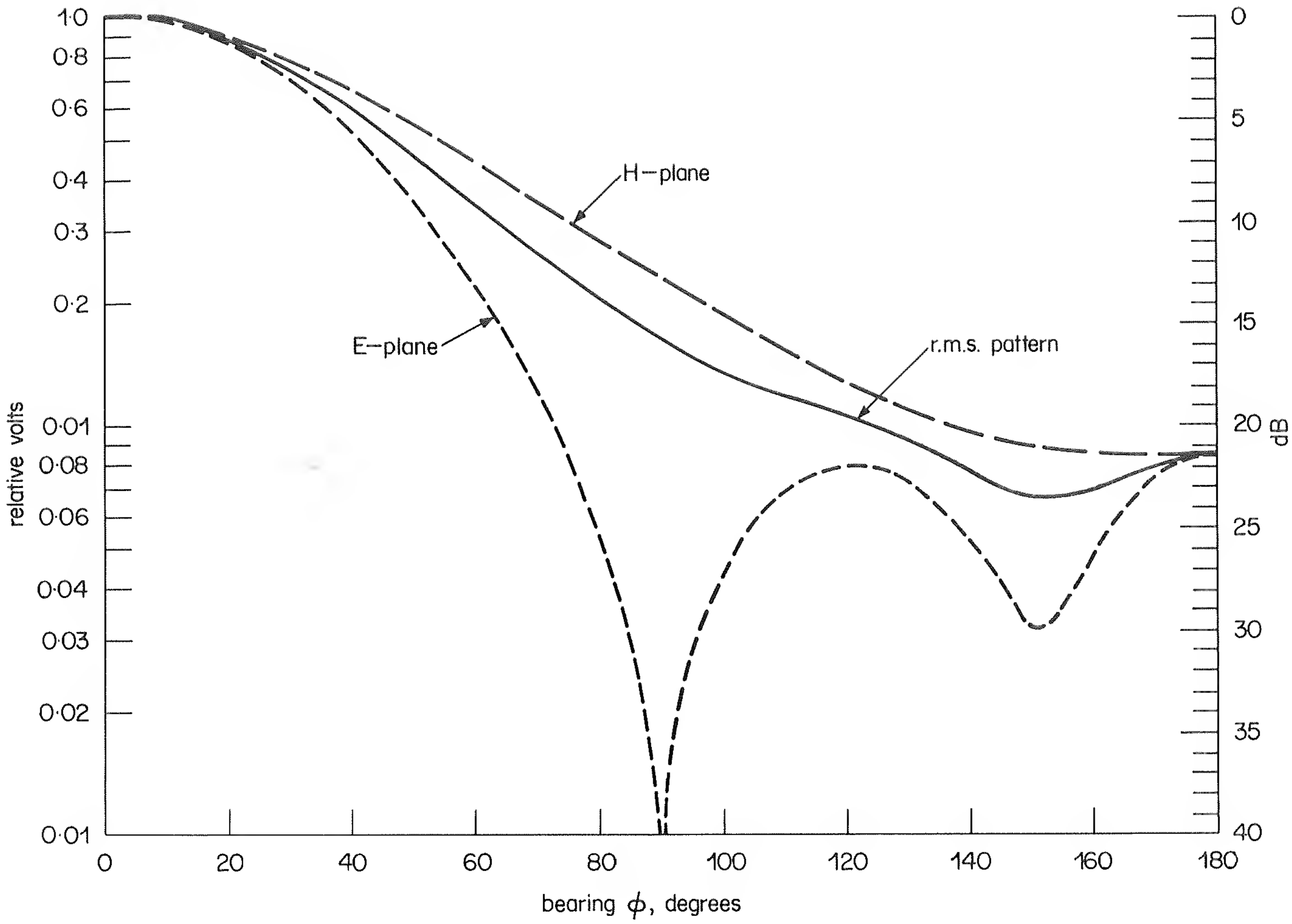

Fig. 5 - Measured radiation patterns of a practical feed antenna

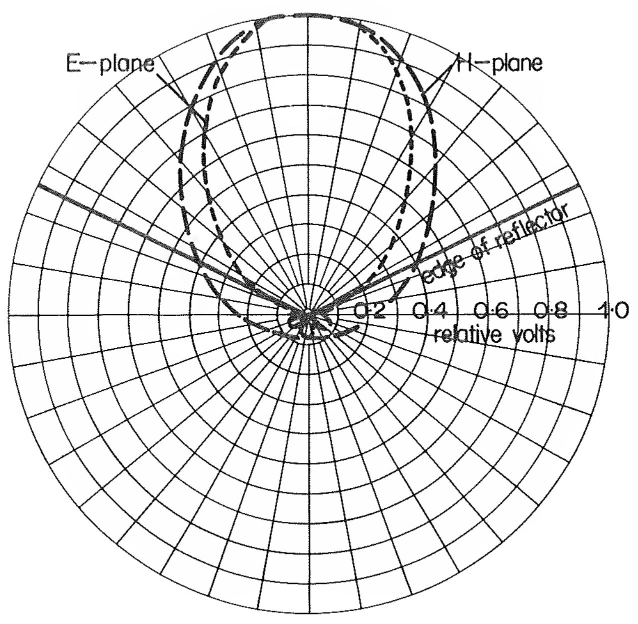

Fig. 6 - Measured radiation patterns of a practical feed antenna in polar form

experimental antenna. The results are shown in Table 2.

TABLE 2

Antenna:	Experi-mental	New Feed
Illumination efficiency η_1	0·872	0·787
Spill-over efficiency η_2	0·798	0·858
$\eta_1 \cdot \eta_2$	0·696	0·675

Thus the new feed antenna has a lower illumination efficiency but a better spill-over efficiency and the products differ by only 0·13 dB. The side-lobe level should, however, be less with the new feed antenna.

7.4. Aperture blocking

The gain available from the reflector aperture will be reduced because part of it is obstructed by the feed. The total area of the reflector aperture is 65·67 square metres but this is not illuminated uniformly. The illumination efficiency is 0·787, so that the effective area is

$$0{\cdot}787 \times 65{\cdot}67 = 51{\cdot}68 \text{ square metres}$$

The projected area of the feed antenna is 0·25 square metres so that the proportion of the total power intercepted by it is

$$\frac{0{\cdot}25}{51{\cdot}68} = 0{\cdot}00484$$

This may be regarded as wide-beamed source in antiphase with the main secondary beam.[1,3] The amplitude of this component is $\sqrt{0{\cdot}00484}$ or 0·07. The normalized main beam is reduced to 0·93 so that the blocking efficiency is given by $\eta_4 = (0{\cdot}93)^2 = 0{\cdot}865$.

7.5. Side-lobe levels

The side-lobe levels of the complete antenna system are considered first, assuming that the spill-over efficiency is unity. The effects of spill-over and aperture blocking are then considered.

An ideal, uniformly-illuminated circular aperture has a first side-lobe level of −17·6 dB. A lower level will be obtained for a tapered distribution. The exact value will depend on the law by which the illumination decreases.[2,3] For the antenna in question, with a level of −8 dB at the edge of the reflector in the H-plane, the side-lobe level will be about −20 dB in the H-plane and about −30 dB in the E-plane. A computation for an illumination tapering linearly to −17 dB (simulating the original feed in the E-plane) gave a first side-lobe level of −32 dB and this pattern is reproduced in Fig. 7.

Those parts of the primary pattern not intercepted by the reflector will contribute to the side-lobe level. First, the backward radiation of the feed will affect the side-lobe over the forward arc of ±90° of the secondary pattern. The two components will add vectorily so that the resultant pattern will be complicated and vary with frequency. It may be seen from Fig. 7, however, that the maximum level of side-lobes will be in the region of −30 dB close to the main lobe dropping

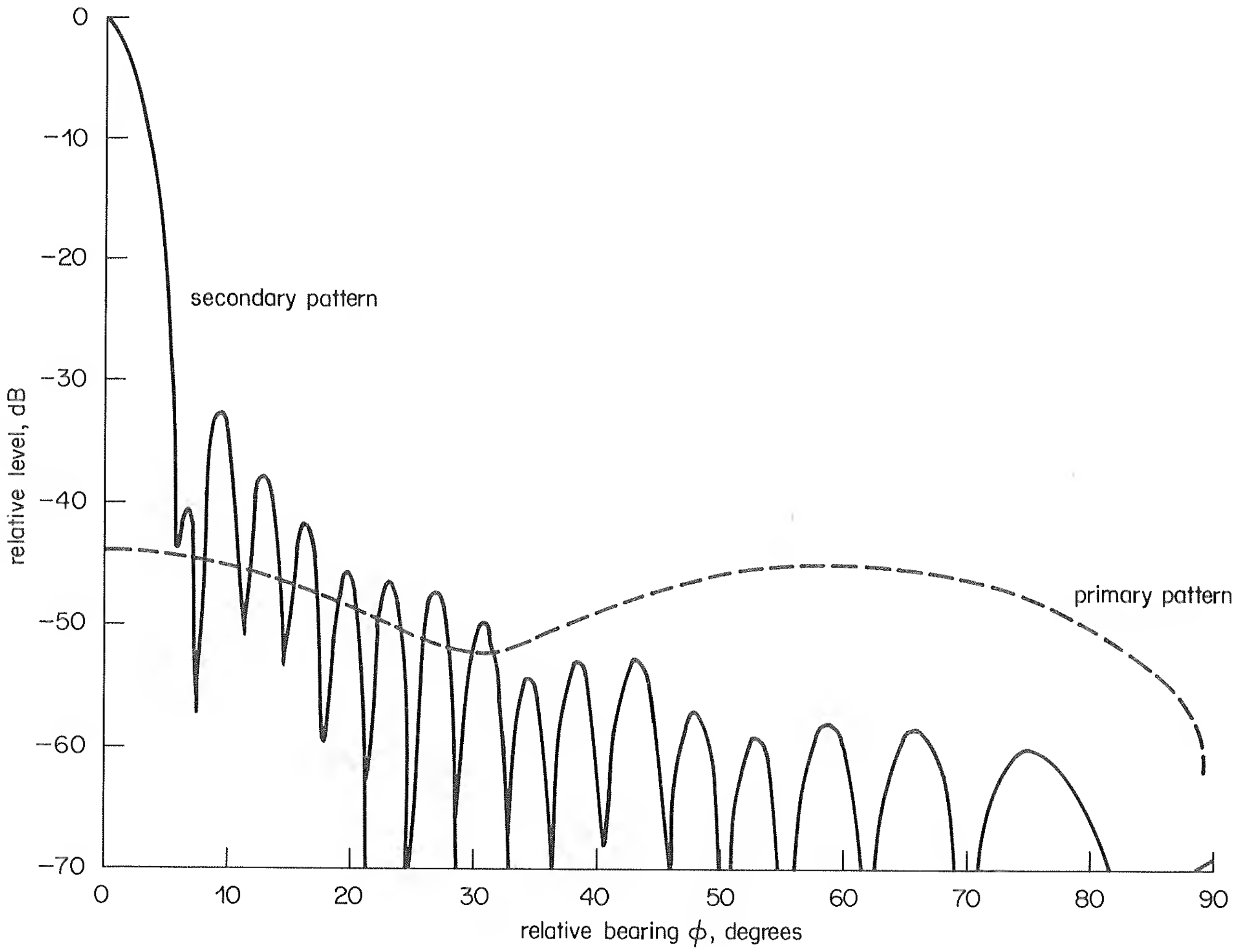

Fig. 7 - Estimation of side-lobe levels for the composite antenna

to −40 dB or −45 dB for the remainder of the forward arc.

Spill-over in the arc 64° – 90° on the feed pattern will affect side-lobe levels in the arc 90° to 116° on the secondary pattern and by diffraction beyond this. The maximum relative level may be crudely estimated at about −38 dB. In the particular application, however, this falls in the arc having terrain screening and so should be unimportant.

Aperture blocking will raise the side-lobe level by an amount estimated as follows.

The area of the obstacle is 0·25 m compared with an effective area of 51·68 square metres for the whole unblocked aperture. The proportion of power intercepted by the obstacle, relative to that intercepted by the unblocked reflector is:

$$\frac{0{\cdot}25}{51{\cdot}68} = 0{\cdot}00484$$

The obstacle may be considered as giving an antiphased component of field of amplitude 0·07. This will reduce the main beam to a level of 0·930 and will raise the level of the first, third and other odd side-lobes in the vicinity of the main beam. Assuming an initial level of −30 dB, the new level becomes

$$\frac{0{\cdot}03 + 0{\cdot}07}{0{\cdot}93} = 0{\cdot}107 \text{ or } -19{\cdot}4 \text{ dB}$$

7.6. Matching

Fig. 8 shows the measured impedance characteristic of the feed antenna in free space. The maximum value of reflection coefficient is about 0·12.

The additional reflection coefficient caused by the presence of the paraboloid when the feed antenna is at the focus, may be calculated from the equation[1]

$$|\Gamma_r| = \frac{G_o\lambda}{4\pi f}$$

where G_o is feed antenna gain
f is the focal length
λ is the wavelength

For the antenna in question, $G_o \approx 9$ and

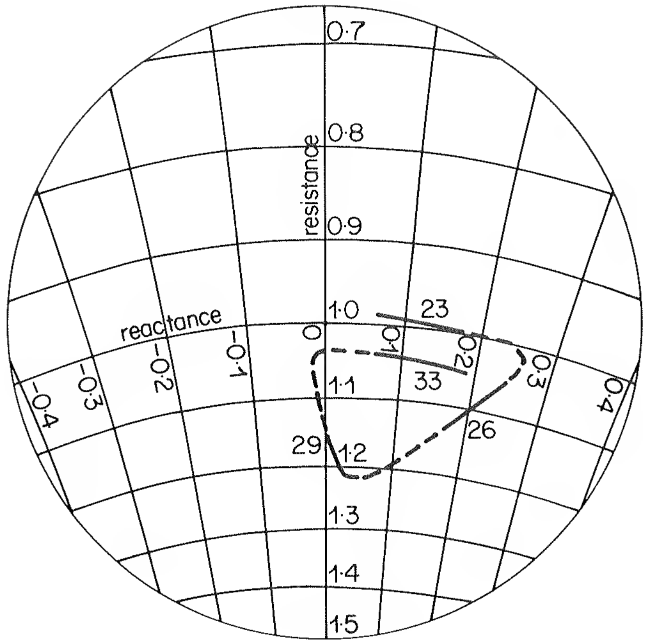

Fig. 8 - Measured impedance of the feed antenna in free space, relative to 50 ohms

The solid parts of the curve relate to the channels whose numbers are adjacent

$$|\Gamma_r| = 0{\cdot}11$$

The two components of the reflection coefficient will add vectorily so that at some frequencies it may reach a maximum value of 0·23. As this is a little higher than the specification a vertex plate may be required. It is suggested that the decision is deferred until the performance of combined antenna can be assessed. The following analysis is included for completeness.

It may be shown[1] that the required diameter of vertex plate is

$$2r = \left(\frac{4f\lambda}{3}\right)^{1/2}$$

and the required thickness is

$$t = (2n + 1)^{\lambda}/4 - \frac{5\lambda}{24}$$

where $n = 0, 1, 2 \ldots\ldots$

Evaluating these formulae for the antenna in question gives

Diameter $2r = 1{\cdot}7$ m
Thickness $t = 23{\cdot}8$ mm

It would be desirable to bond the edge of the plate to the reflector but this may be inconvenient if the reflector is pre-painted.

The above analysis gives the diameter of vertex plate required for full correction of the impedance effect. However, such a plate would have a deleterious effect on the radiation pattern and gain. It is proposed, therefore, to use the smallest diameter of plate that will just meet the impedance requirement. This is likely to be about half the diameter given above.

The effect of the vertex plate on the antenna gain may be estimated in the same way as aperture blocking. Since the portion of aperture affected is the same, only the additional area affected by the vertex plate will be assessed.

A plate of radius 0·425 m has an area of 0·567 m and the proportion of power falling upon it is 0·0109 of the total. This will give a relative field of 0·105 in antiphase with the main beam, which will be reduced to 0·895. The corresponding value of efficiency is 0·801. However, an efficiency of 0·865 was computed for the blocking of the aperture. The additional factor is therefore

$$\frac{0{\cdot}801}{0{\cdot}865} = 0{\cdot}926.$$

7.7. Efficiency and gain

The component efficiencies may now be taken to provide an estimate of the overall efficiency and therefore of the antenna gain. For this purpose the loss in the coaxial feeder will be disregarded. The component efficiencies have the following estimated values

$$\begin{aligned}
\eta_1 &= 0{\cdot}787 \\
\eta_2 &= 0{\cdot}858 \\
\eta_3 &= 0{\cdot}99, \text{ say} \\
\eta_4 &= 0{\cdot}865 \\
\eta_5 &= 1{\cdot}000 \pm 0{\cdot}014 \\
\eta_6 &= 0{\cdot}926 \\
\eta_7 &= 0{\cdot}96 \text{ minimum} \\
\eta_8 &= 1{\cdot}00 \\
\eta_9 &= 1{\cdot}00 \\
\eta_{10} &= 0{\cdot}99, \text{ say} \\
\eta_{11} &= 0{\cdot}99, \text{ say}
\end{aligned}$$

The overall efficiency is the product of these. Taking η_5 at its mid-value (1·00) we find

Antenna efficiency = 0·504

The maximum efficiency obtainable with a front-fed paraboloid is thought to be about 0·65 and the EIA Standard figure is 0·55. A value of 0·5 is considered acceptable for an aperture of only sixteen wavelengths. The design of feed should therefore prove satisfactory.

The gain of the uniformly illuminated aperture is[1]

$$G = \left[\frac{\pi D}{\lambda}\right]^2$$

which evaluates to 34·7 dB relative to an isotropic source for the antenna under consideration at Channel 33. The expected practical gain is then

31·7 dB relative to an isotropic source
29·6 dB relative to a dipole

If the vertex plate can be dispensed with, the antenna efficiency becomes 0·544 and the gains become

32·1 dB relative to an isotropic source
30·0 dB relative to a dipole

8. Conclusions

A feed antenna has been designed for use with a 9·14 m diameter paraboloidal reflector having a focal length/diameter ratio of 0·4. Two antennas have been produced to this design but, owing to delay in the erection of the reflector, have not yet been installed. It is predicted that the efficiency of the feed will be in excess of 50%, and that the system gain will be greater than 31 dB relative to an isotropic source.

SMW/SB

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